Evaluation of the possibility of using atmospheric information derived from a high performance imaging system for short-range weather forecasting

Su Jeong Lee[1], Myoung-Hwan Ahn[1],
Sung-Rae Chung[2]

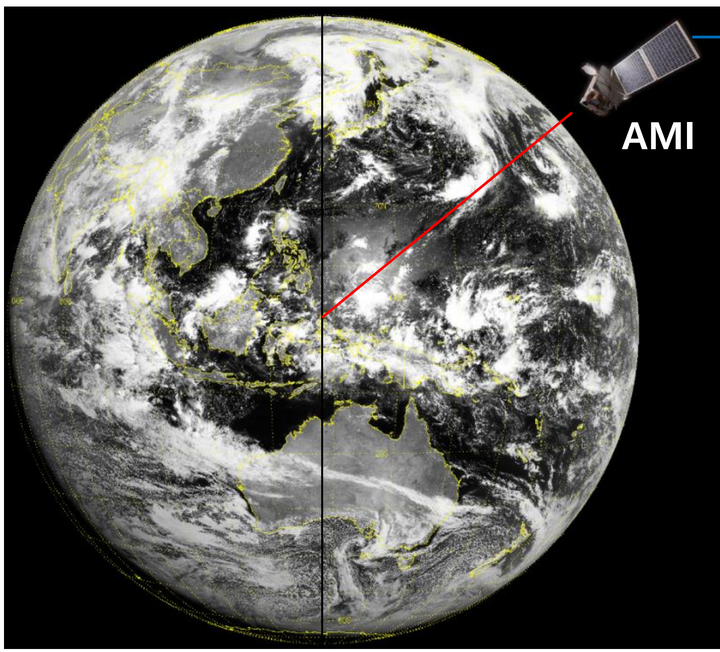
1. Department of Atmospheric Sciences and Engineering, Ewha Womans University
2. National Meteorological Satellite Center

The 7th Asia-Oceania/2nd AMS-Asia/ 2nd KMA Meteorological Satellite Users' Conference

AMI Atmospheric Profile (AAP) retrieval algorithm

- **Purpose:** Retrieval of clear-sky atmospheric profiles from AMI
- **Measurements**: Brightness temperature at 8 IR channels (6.2, 6.9, 7.3, 9.6, 10.4, 11.2, 12.4, 13.3 μm)
- **Retrieval products:** vertical Temperature(T) / Moisture(Q) profiles
- **Derived products:** Total Precipitable Water (TPW), Total Ozone(TOZ), Stability indices (5 kinds)

GeoKOMPSAT-2A (2018~)



128E

* GK-2A (Geo-KOMPSAT 2A)
* AMI (Advanced Meteorological Imager)

Level 1B

IR Ch.
6.2
6.9
7.3
8.6
9.6
10.4
11.2
12.4
13.3

algorithm

Clear-sky products

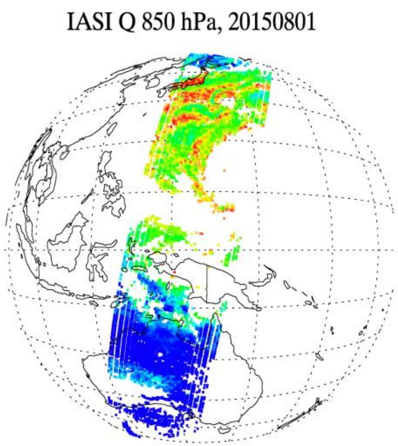
- T/Q profile
- TPW
- TOZ
- Stability indices
  - ✓ K-index
  - ✓ Lifted index
  - ✓ Showalter index
  - ✓ Total Totals
  - ✓ CAPE

Introduction

Advantage of Geo-imager-derived products
- to fill the gaps between measurements
- to capture rapidly developing and decaying

Retrieval accuracy
- on-going analysis and experiments on performance factors (quality/type of input data, algorithm parameters) that need to be considered

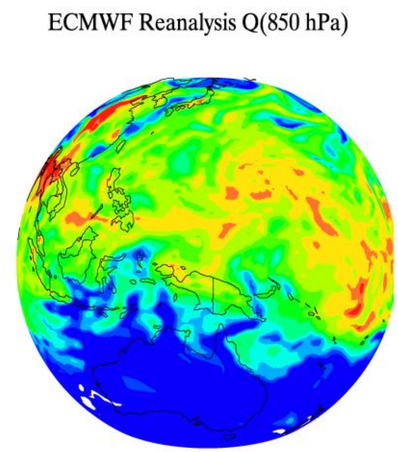
Polar orbiting hyper-sounder



2/day

4×12km (center)

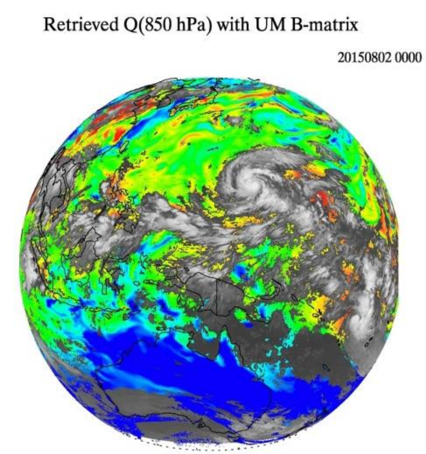
NWP forecast



Every hour

≥ 10km

Geostationary imager



Every 10 minutes

≥ 2km (6km)

Algorithm Outline

- Retrieval scheme: **iterative physical retrieval** with **optimal estimation(OE)**
  - ✓ **Minimize Cost function**

$$J = \underbrace{[y - F(x)]^T S_\varepsilon^{-1} [y - F(x)]^T}_{\text{Obs+RTM}} + \underbrace{[x - x_a]^T S_a^{-1} [x - x_a]}_{\text{background}} \longrightarrow \frac{\partial J}{\partial x} = 0$$

  - ✓ **Gauss-Newton Method** for moderately nonlinear retrieval problem

$$x_{i+1} = x_i - [\nabla_x\, g(x_i)]^{-1}\, g(x_i)$$

(Rodgers, 1976; Rodgers, 2000)

  - ✓ **Iterative solution**

$$\boxed{x_{n+1} = x_0 + (S_a^{-1} + K_n^T \cdot S_\varepsilon^{-1} \cdot K_n)^{-1} \times K_n^T \cdot S_\varepsilon^{-1} \left[T_B - T_{B,n} + K_n \cdot (x_n - x_0)\right]}$$

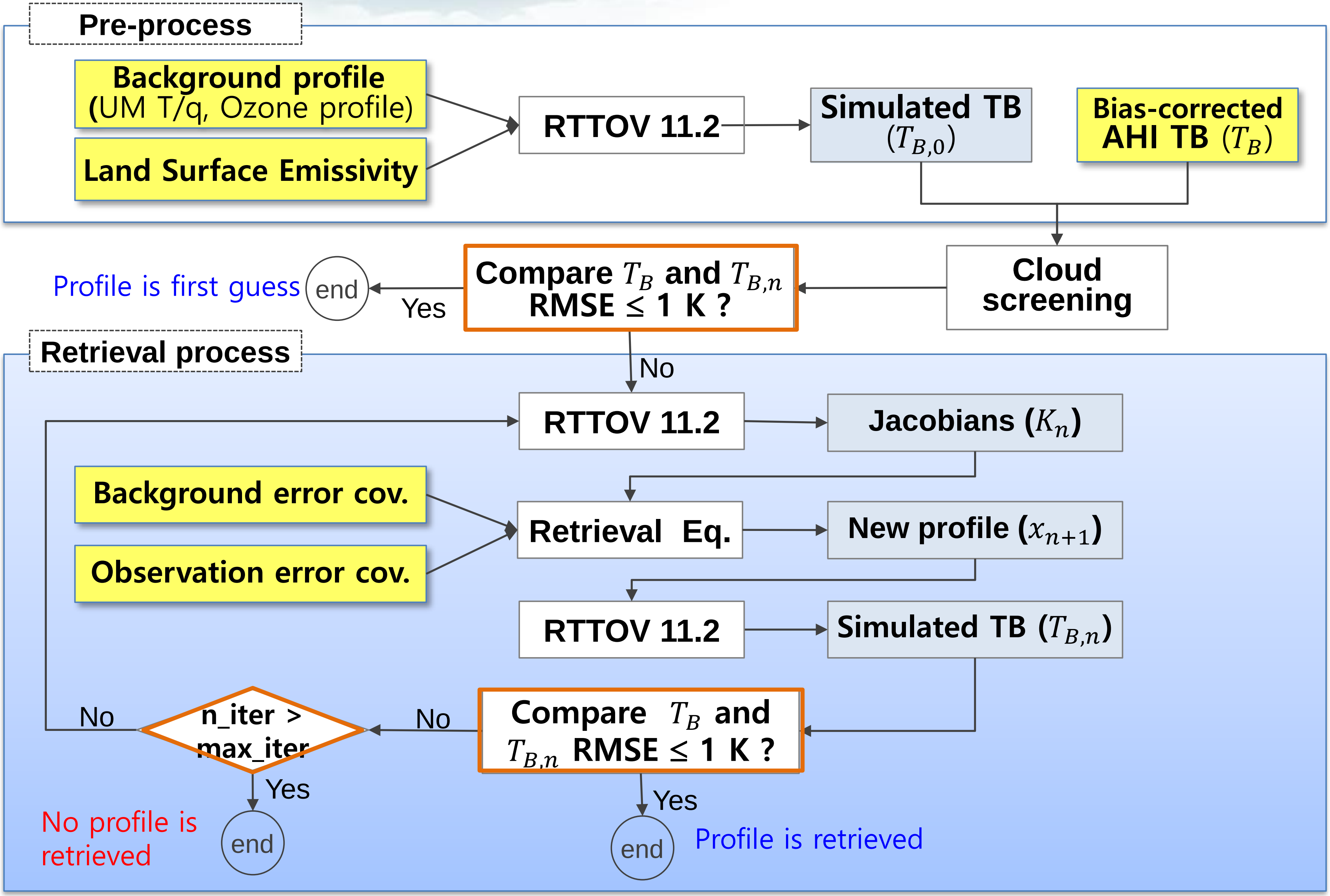
n	iteration step
x_0	background profile
x_n , x_{n+1}	the previous and current solutions (atmospheric profiles)
T_B	observed brightness temperature
$T_{B,n}$	simulated brightness temperature for profile of iteration step n
K_n	Jacobian matrix at iteration step n
S_a	error covariance matrix of background
S_ε	error covariance matrix of observed TB and of RTM

Data

$$x_{n+1} = x_0 + (S_a^{-1} + K_n^T \cdot S_\varepsilon^{-1} \cdot K_n)^{-1} \times K_n^T \cdot S_\varepsilon^{-1}(T_B - T_{B,n} + K_n \cdot (x_n - x_0))$$

- **Observation (T_B)**: Radiance measured from AHI 8 (6.2, 6.9, 7.3, 9.6, 10.4, 11.2, 12.4, 13.3 μm) infrared channels, converted to brightness temperature
- **Observation error covariance (S_ε)**: AHI NEdT (WMO, OSCAR)
- **Background or First Guess profile (x_0)**:
  - ✓ **Temperature and moisture:** short-range (6-11 hr, 1hr interval) forecast from KMA Global prediction model based on UK Met-office Unified Model (UM)
  - ✓ **Ozone profile**: ozone profile created from monthly climatology (McPeters, and Labow, 2017) and satellite-derived total ozone (OMI/OMPS)
- **Background error covariance (S_a)**:
  - ✓ **Temperature and moisture**: B-matrix used in NWPSAF 1DVAR system
  - ✓ **Ozone**: B-matrix for ECMWF 1DVAR
- **Land Surface Emissivity (LSE)**: monthly climatology created from 12 years (2003-2014) of UW-Madison baseline fit global emissivity database (Seemann et al., 2007)

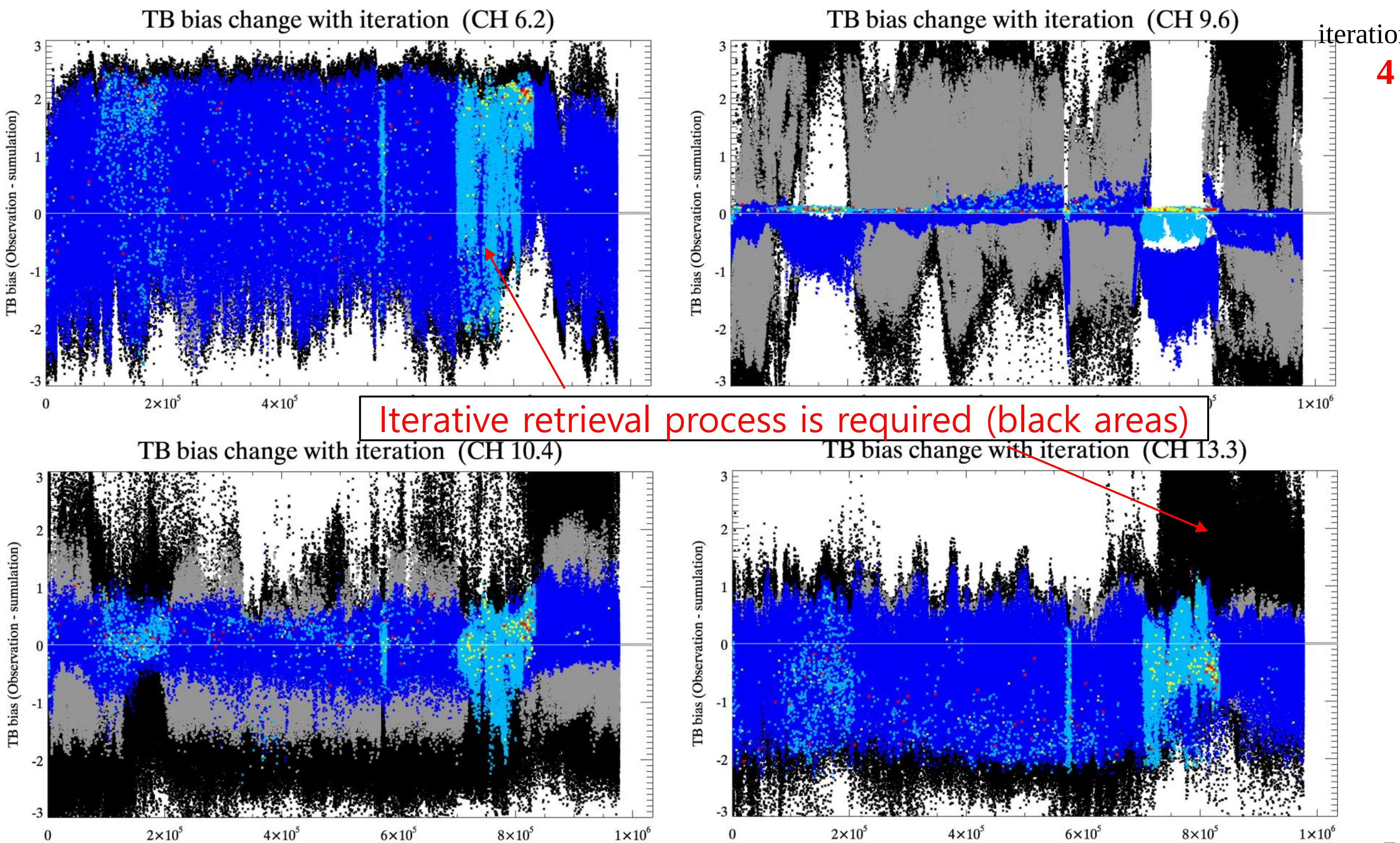
Algorithm flowchart



Algorithm characteristics

➢ Change of TB bias (Obs. – simulation) with iteration

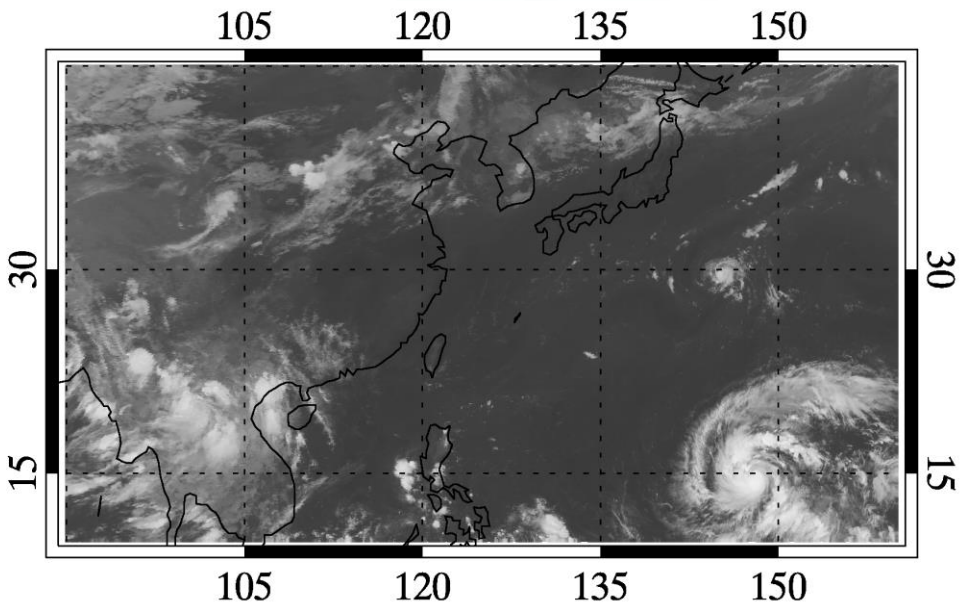
About 3% of cloud-free pixels succeed to retrieve profiles with more than 1 iteration



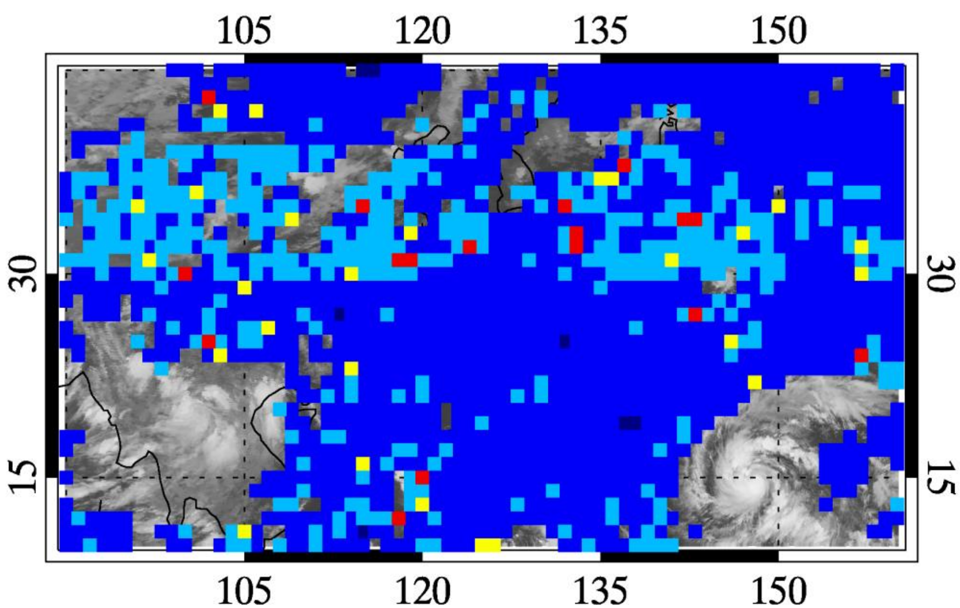
* Analyzed scene: 20150802 0000 UTC

Algorithm characteristics

➢ **Iteration map**



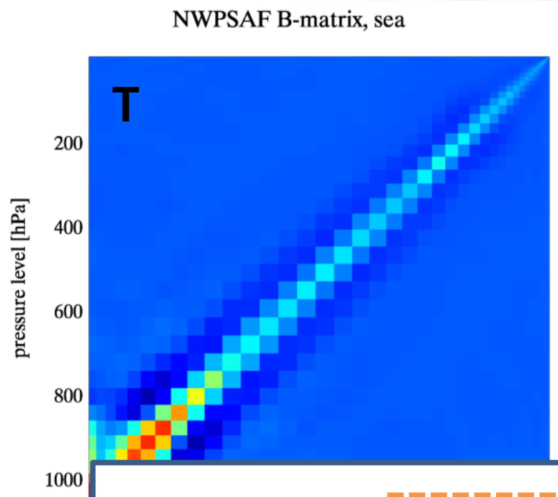
10.4 TB image

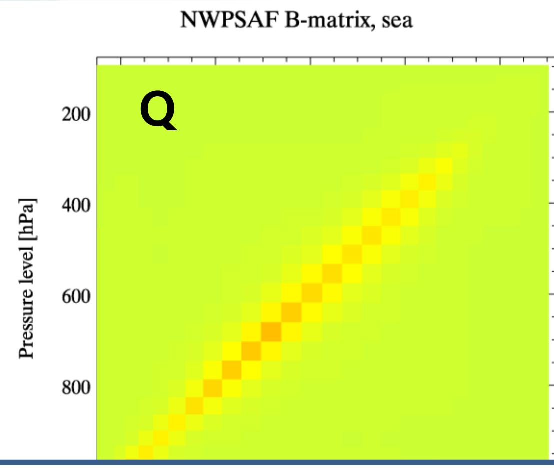


Pixel successfully retrieve profiles

- without iteration
- with 1 iteration
- with 2 iterations
- with 3 iterations
- with 4 iterations

Performance factors – error covariance

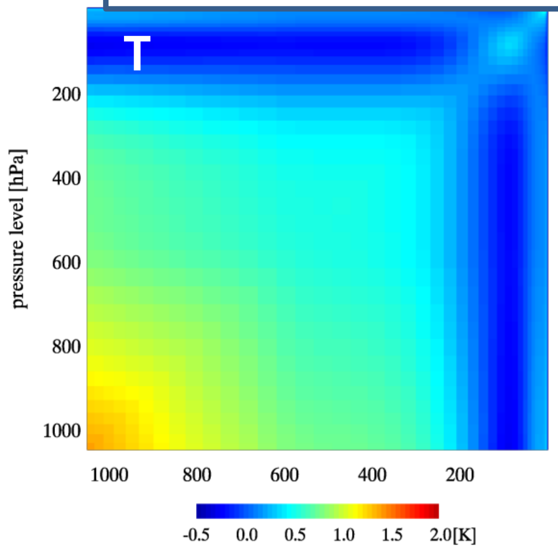


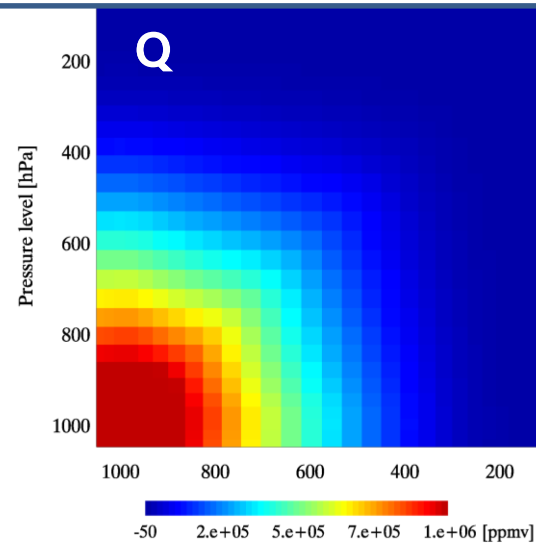


NWPSAF(UM) B-matrix

- Large diagonal components
- near-zero cross correlation between errors in two different pressure levels

$$x_{n+1} = x_0 + \underbrace{\left(S_a^{-1} + K_n^T \cdot S_\varepsilon^{-1} \cdot K_n\right)^{-1} \times K_n^T \cdot S_\varepsilon^{-1}\left[T_B - T_{B,n} + K_n \cdot (x_n - x_0)\right]}_{\text{increment } (\delta x)}$$



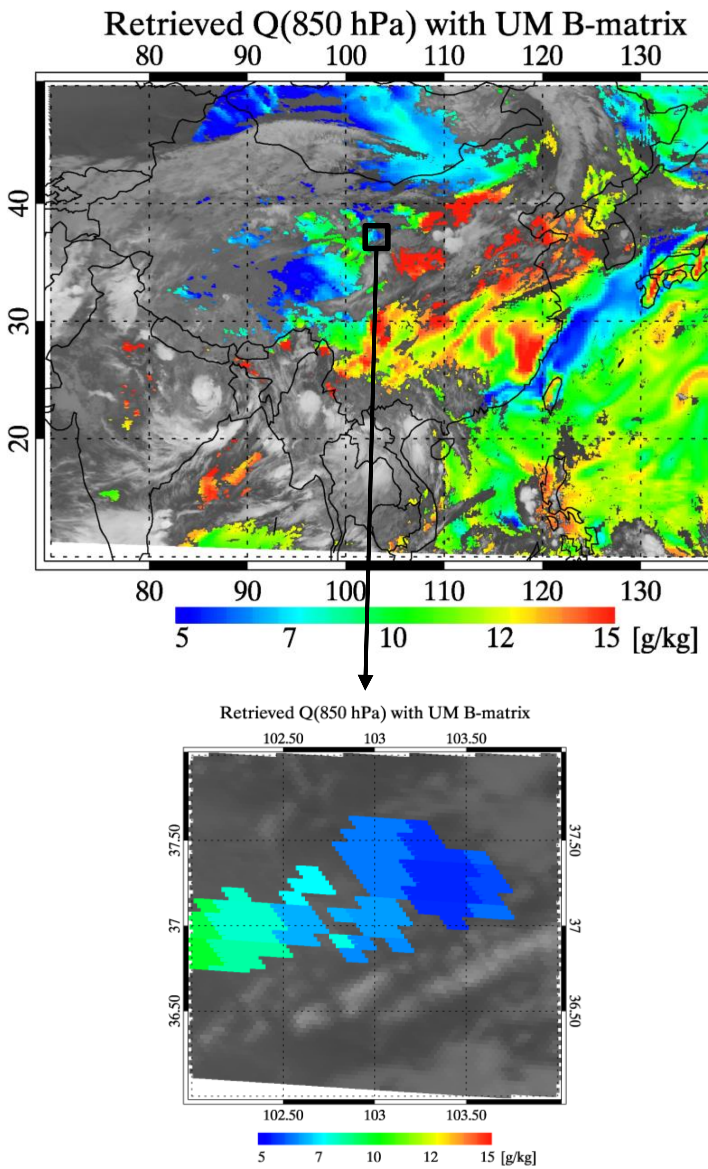


ECMEF B-matrix

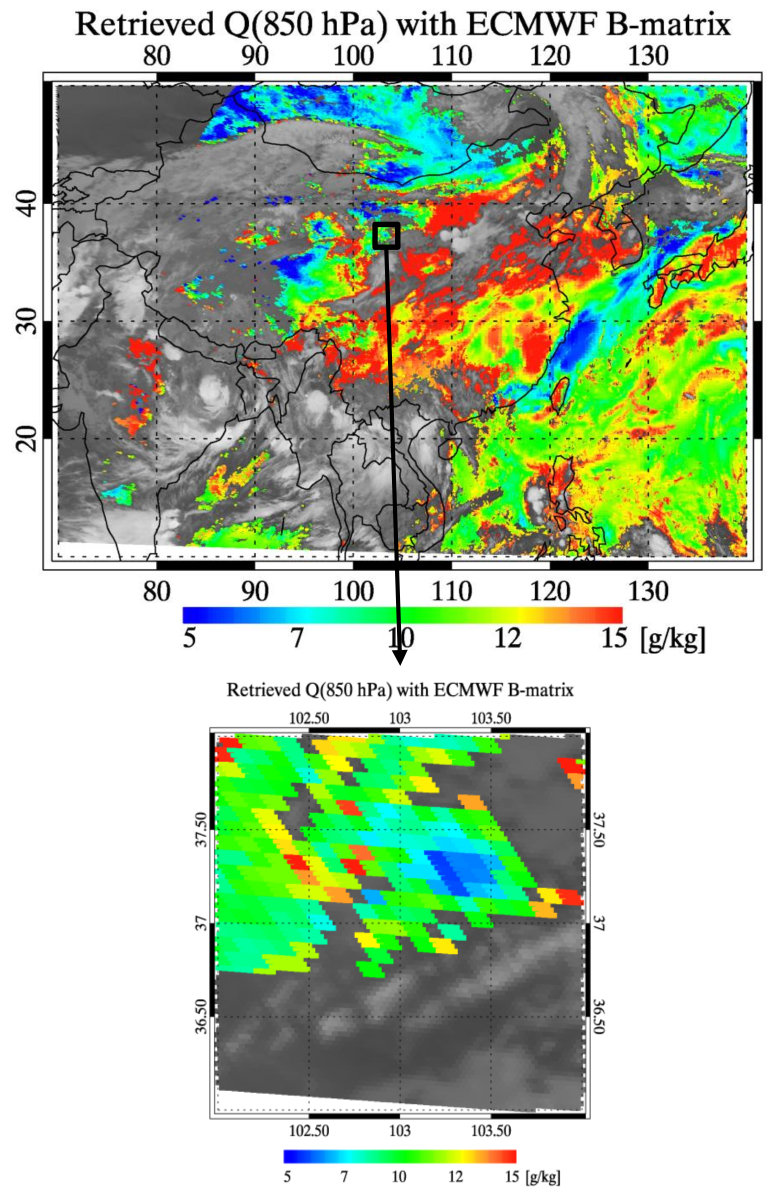
- cross-covariance between error in different levels (off-diagonal components) are relatively high up to 200 hPa for temperature and 500 hPa for moisture

Performance factors – error covariance

NWPSAF(UM) B-matrix



ECMEF B-matrix

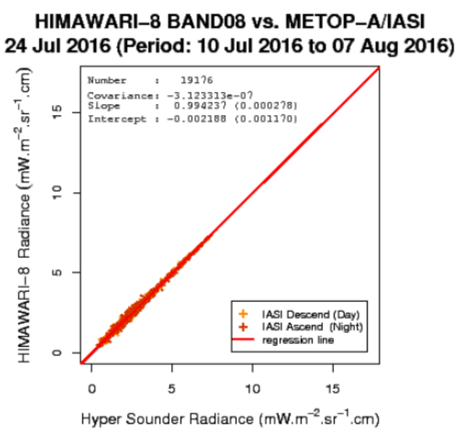


Performance factors – unbiased observation

$$x_{n+1} = x_0 + (S_a^{-1} + K_n^T \cdot S_\varepsilon^{-1} \cdot K_n)^{-1} \times K_n^T \cdot S_\varepsilon^{-1} \left[T_B - T_{B,n} + K_n \cdot (x_n - x_0)\right]$$

* assumption: radiance data does not have a **systematic bias**

- Used **GSICS* correction** to remove systematic bias in AHI data JMA (2016)



Radiance (AHI) = $\mathbf{C_0}$ + $\mathbf{C_1}$ × Radiance (hyper sounder)

C_1 : Slope,

C_0 : Intercept

Corrected radiance (AHI) = [HSD radiance (AHI) - $\mathbf{C_0}$] / $\mathbf{C_1}$

- Calculated **mean C0 and C1** from Jul 1 2015 to Jul 24, 2016 (388 days in total)

Channel	6.2	6.9	7.3	8.6	9.6	10.4	11.2	12.4	13.3
C_0 (intercept)	-8E-04	-0.021	-0.175	0.058	0.17	0.375	0.289	0.416	0.428
C_1 (slope)	0.993	0.996	1.009	0.998	0.991	0.996	0.998	0.995	0.997

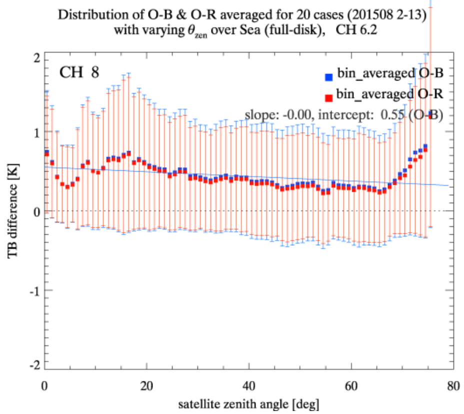
*GSICS: Global Space-based Inter-Calibration System

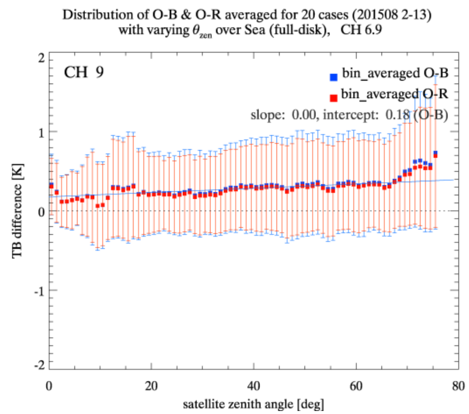
Performance factors – unbiased observation

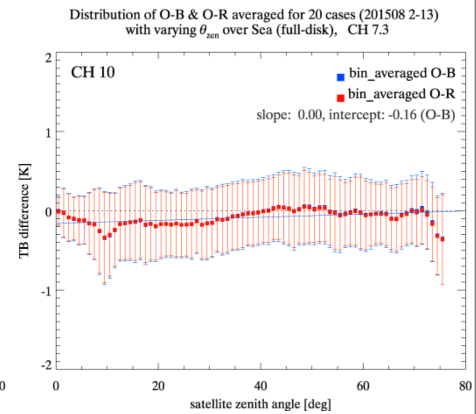
- **O-B vs. Obs.-Ret. with varying satellite zenith angle (with error bars)**

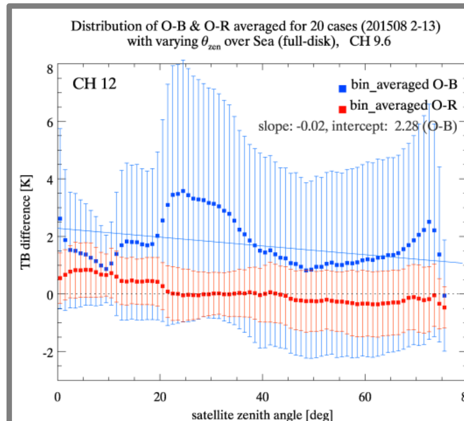
* Analyzed data: 20 scenes from 1~13 Aug. 2015 (12hr interval), clear-sky, ocean full-disk

Before Bias Correction





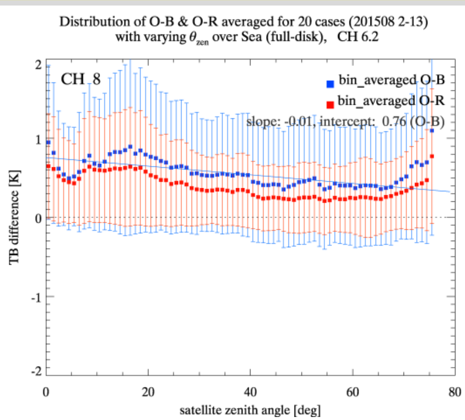


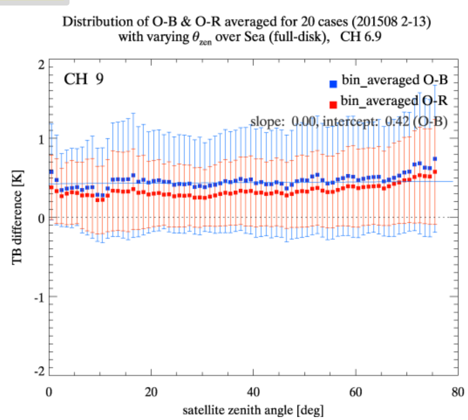


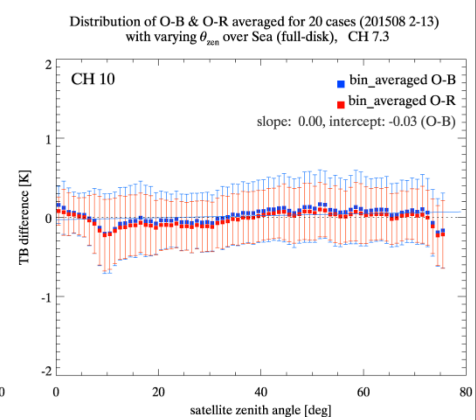
Water vapor absorption channels

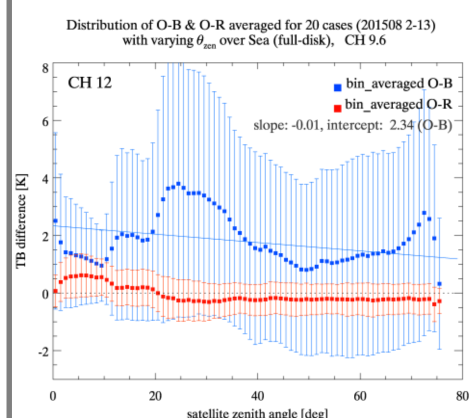
O_3 absorption

After Bias Correction







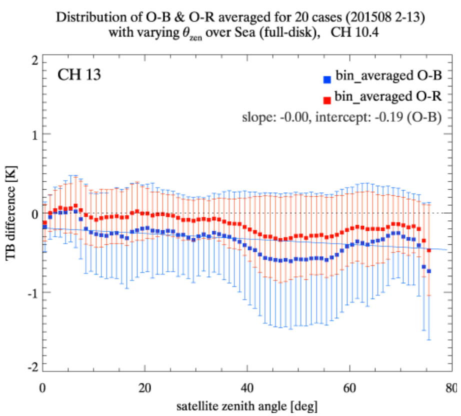


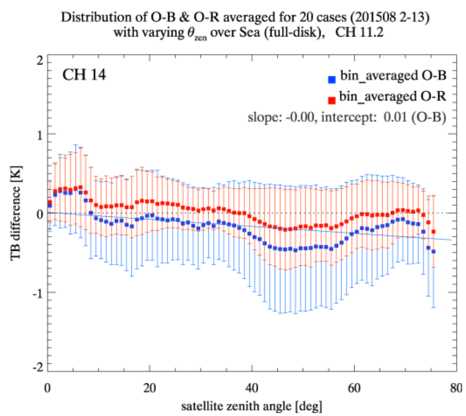
Performance factors – unbiased observation

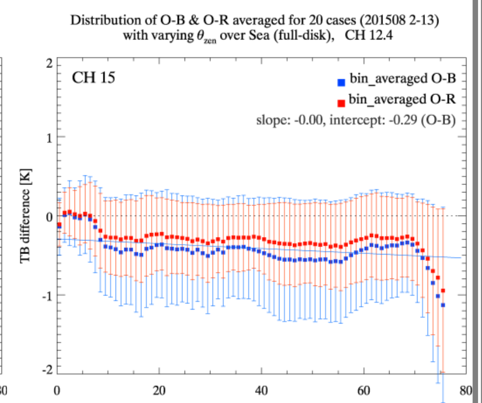
- **O-B vs. Obs.-Ret. with varying satellite zenith angle (with error bars)**

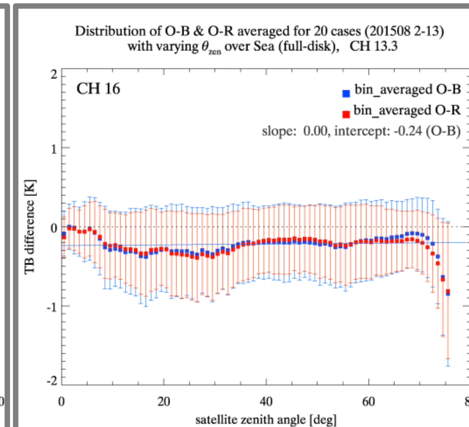
* Analyzed data: 20 scenes from 1~13 Aug. 2015 (12hr interval), clear-sky, ocean full-disk

Before Bias Correction





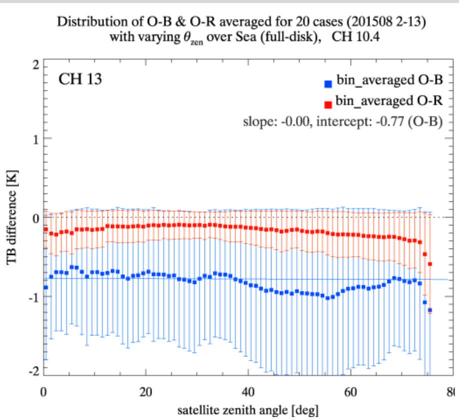


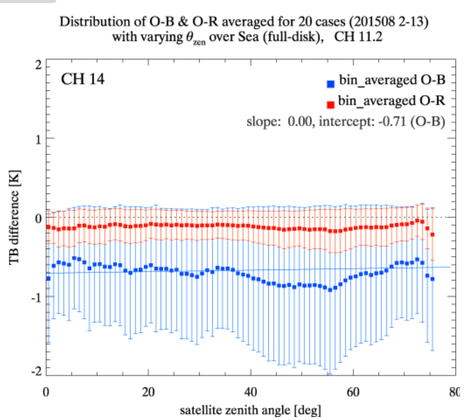


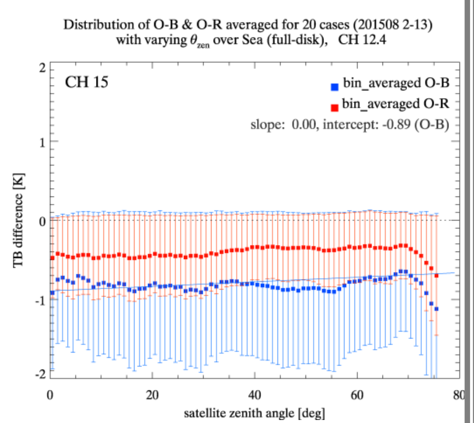
Window channels

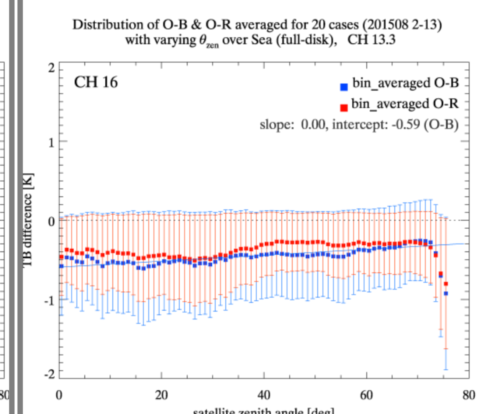
CO_2 absorption

After Bias Correction





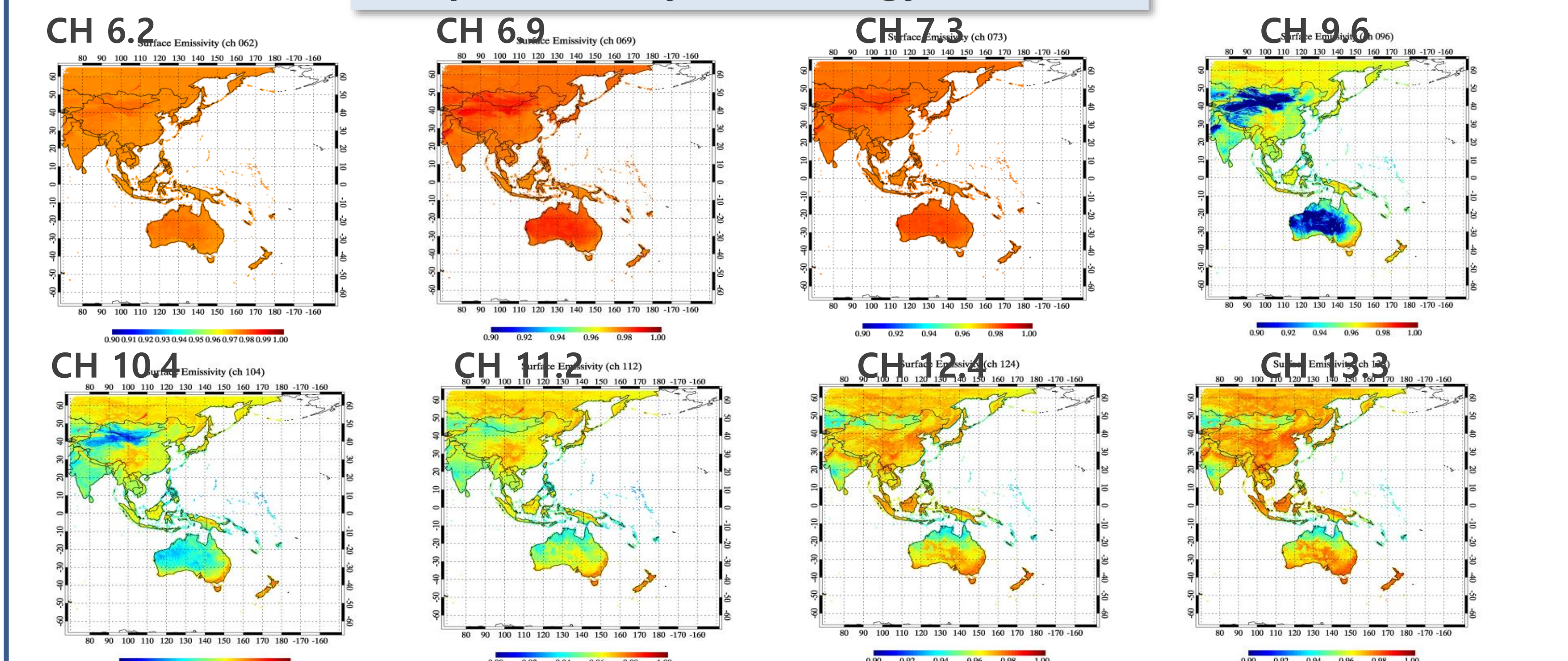




Performance factors – land surface emissivity

- **Accurate land surface emissivity data is essential for the simulation of accurate brightness temperature particularly for the channels sensitive to the surface**
- **Currently available data:** baseline fit Global infrared land surface emissivity database developed at the CIMSS (Seemann et al., 2007)
- **Created monthly climatology** from the database of 12 years (2003-2014) and **interpolated to AHI** infrared channels using Akima spline interpolation

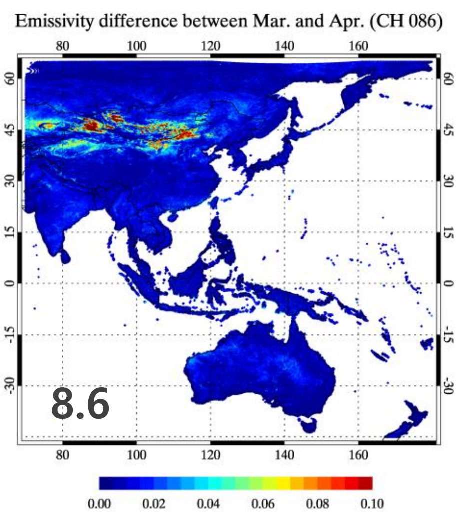
Sample: Monthly Climatology for June

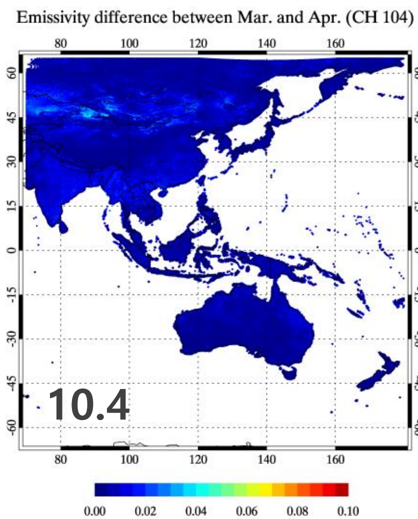


Performance factors – emissivity

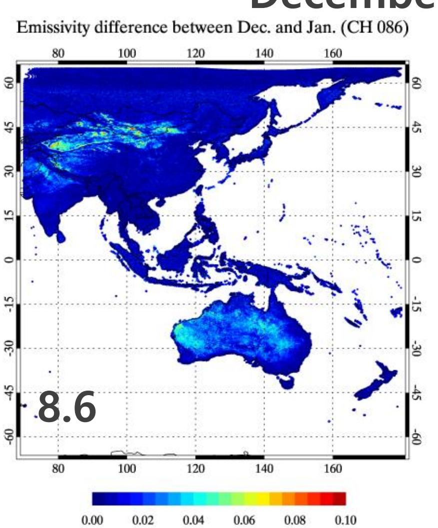
- Need to deal with **inter-month variability** of the monthly climatology

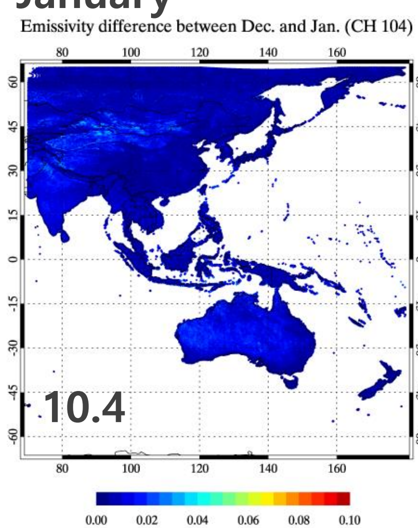
March ~ April





December ~ January



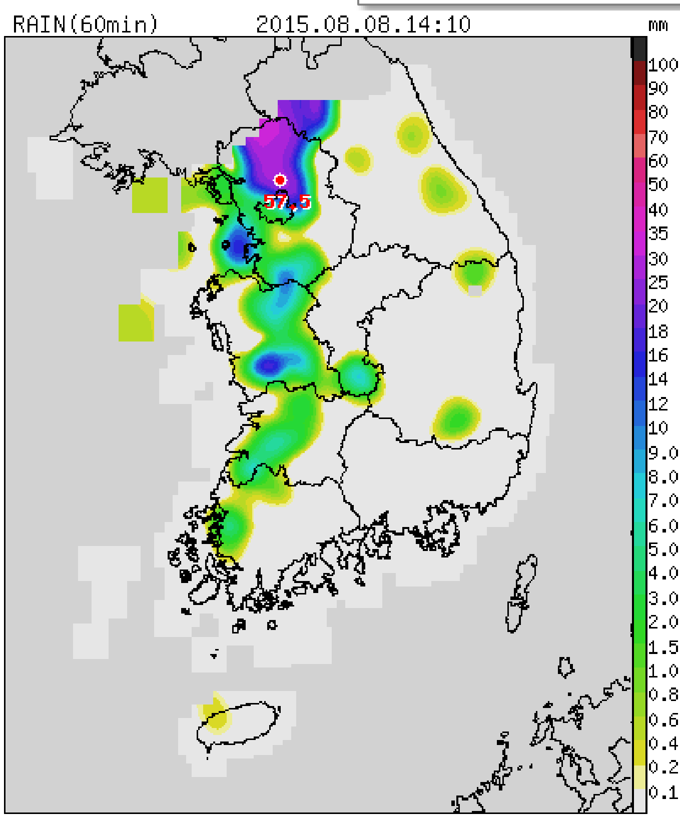


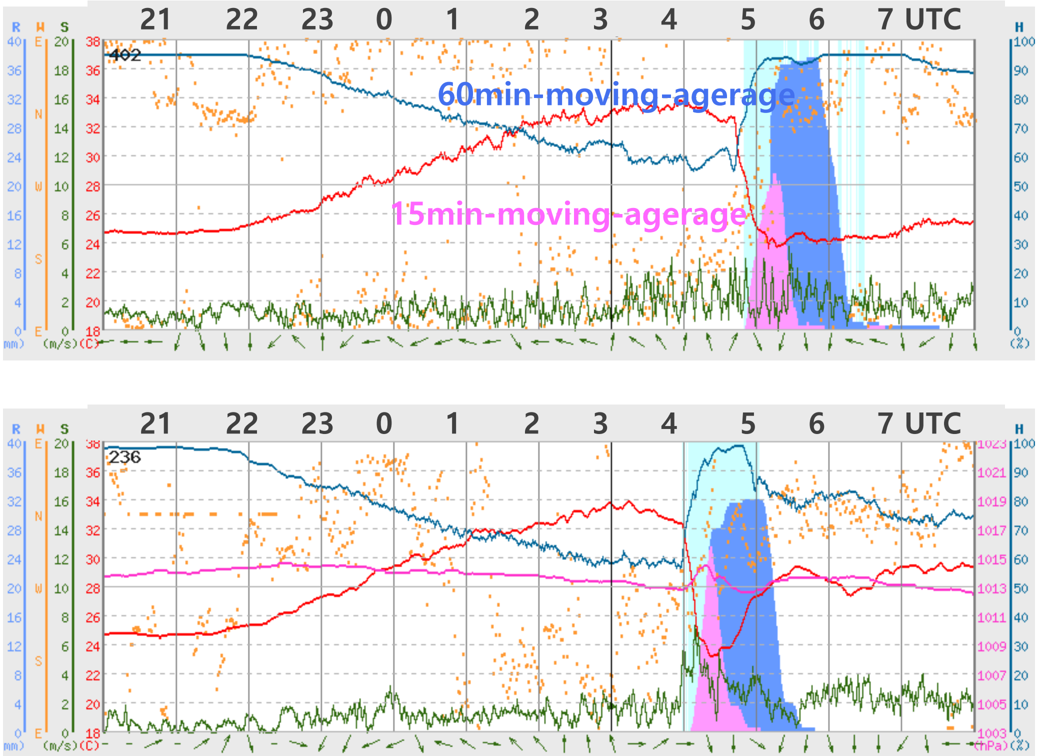
- ✓ Inter-month variability is particularly large between Mar. and Apr. and Dec. and Jan. for channel 8.6 and 10.4 in arid areas in East Asia
- ✓ the largest difference up to 0.1 is shown between Mar. and Apr. for channel 8.6
- ✓ Interpolation for the time domain (e.g., ±5 days)is required to reduce the variability

Case study: severe weather

- Severe weather event associated with thermo-dynamically unstable atmospheric condition
- Date: Aug. 08, 2015 (04 UTC~)
- Rainfall: max 57.5mm /hour (28 mm /15min) around Seoul area

Ground-station measurements (rainfall)



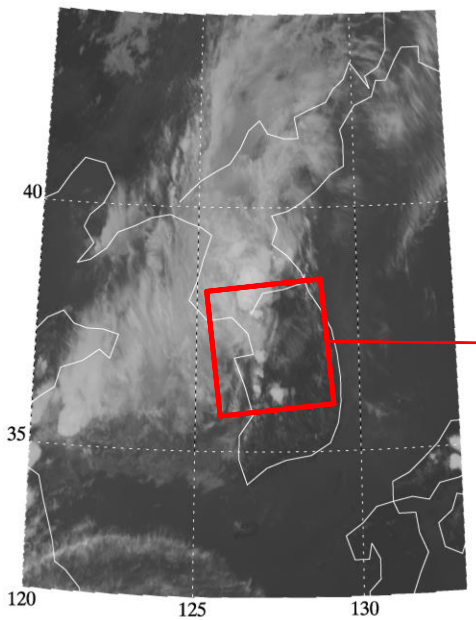


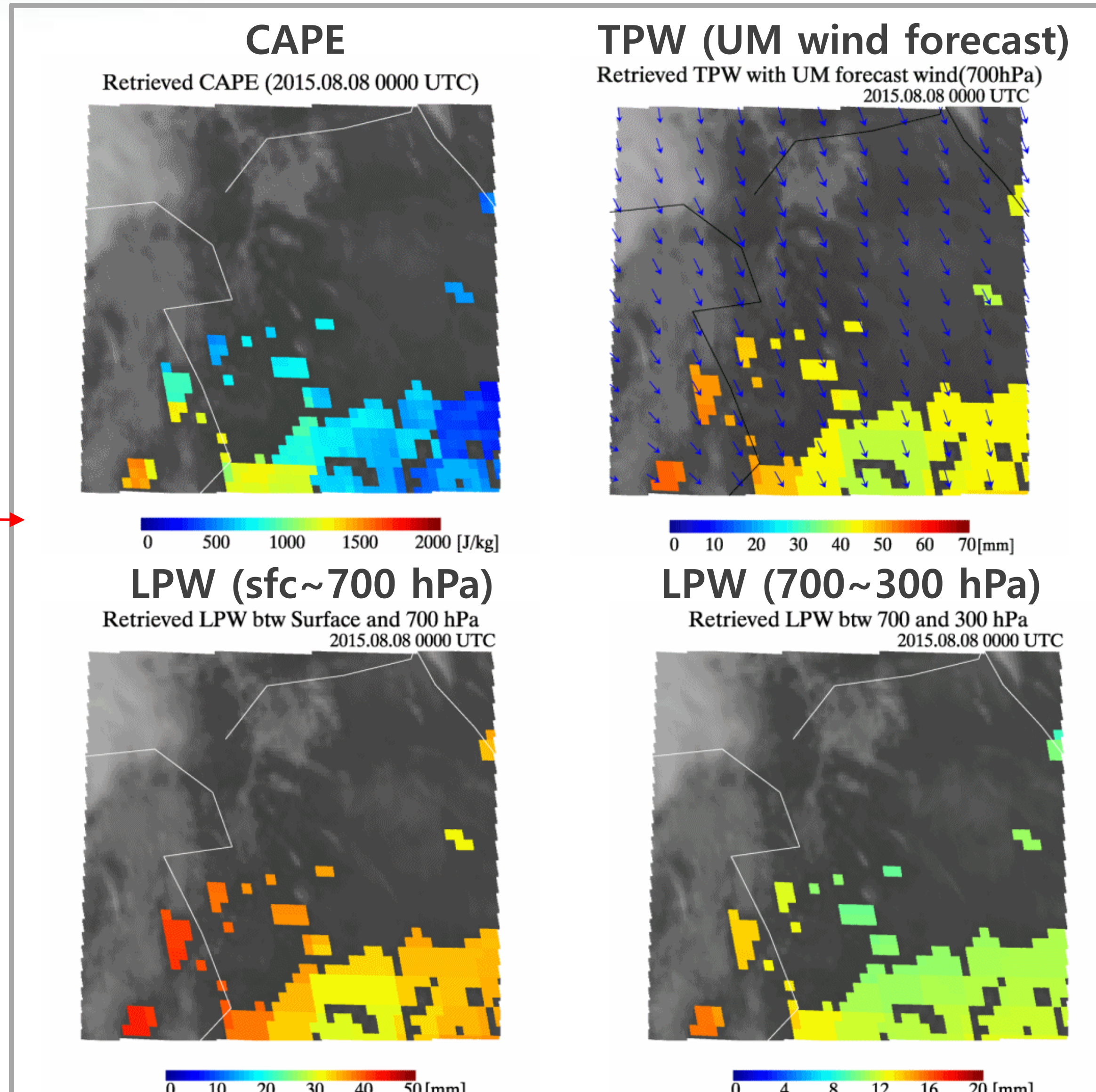
Case study: severe weather

Retrieved products

10.4 AHI TB image

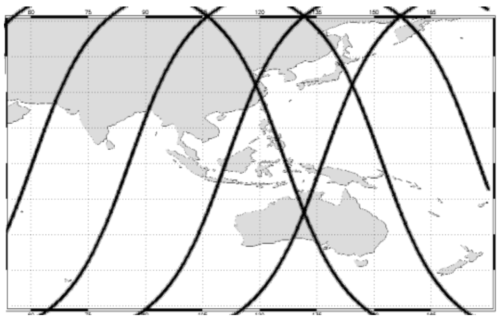
2015.08.08 0350 UTC

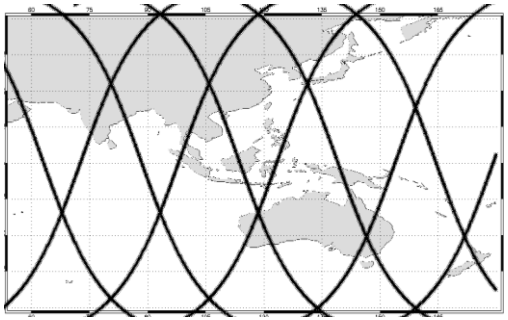


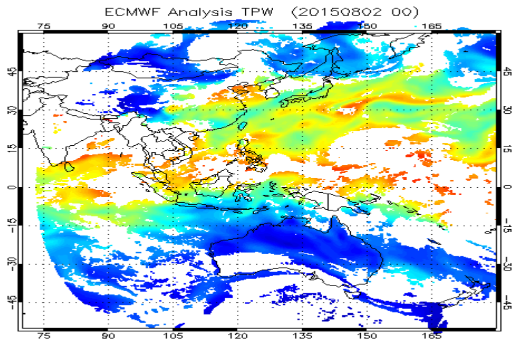


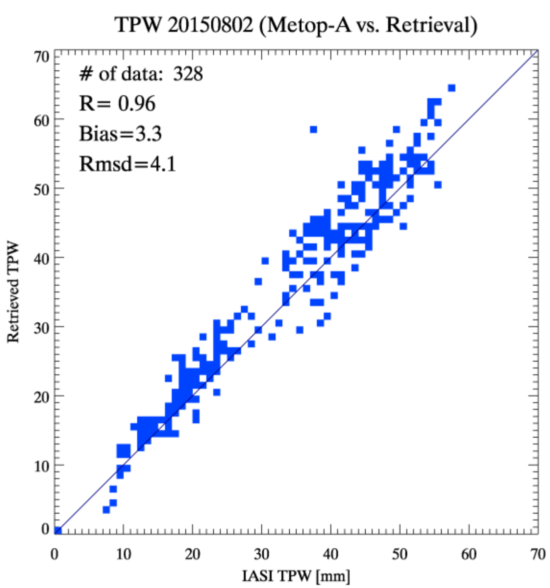
Validation (TPW)

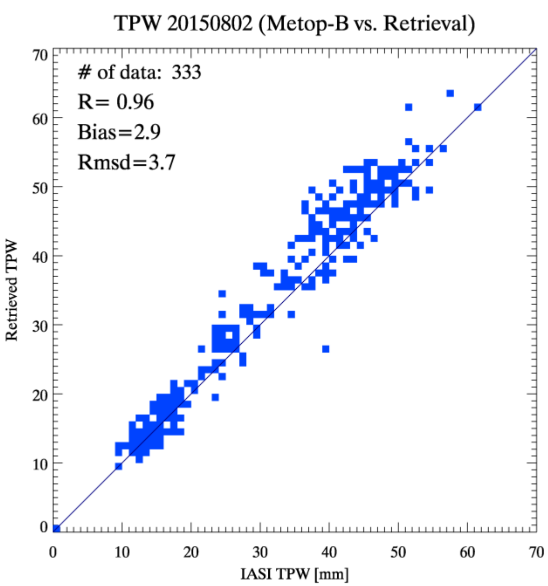
Product compared: TPW
Data used: 02 Aug., 2015
Reference data: TPW from IASI on-board Metop-A (left), Metop-B(middle), and ECMWF analysis

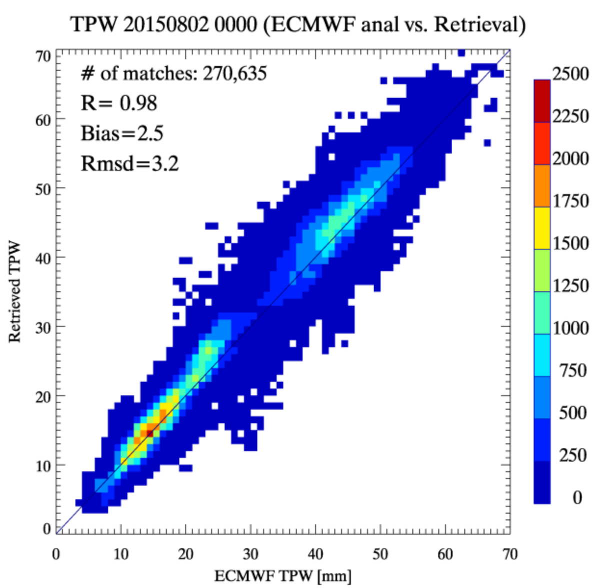




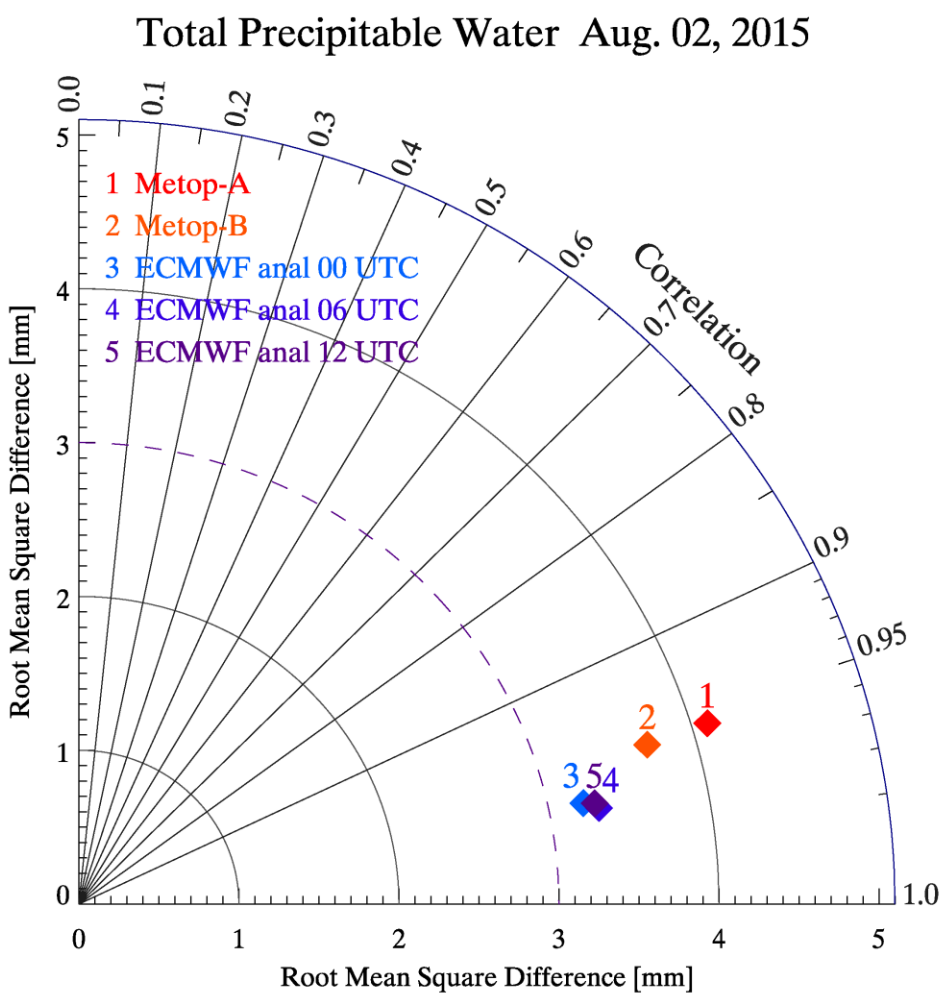








Validation (TPW)



- ✓ Required accuracy for TPW
  Bias: 1 mm
  RMSE: 3 mm
- ✓ Shows better agreement with ECMWF analysis (for three cases, 00/06/12 UTC) than IASI TPW
- ✓ Shows better agreement with TPW from IASI onboard MetopB than Metop-A
  *launch
  Metop-A: Oct. 2006
  Metop-B: Sep., 2012

Need to get reliable validation results with sufficient amount of data and for various cases

Summary

- AAP (AMI Atmospheric Profile) algorithm has been developed to retrieve clear-sky atmospheric T/q profiles and TPW, TOZ, instability indices from Korea's second generation imager.
- Algorithm configuration:
  - ✓ Sensor data: AHI radiance from 8 infrared channels
  - ✓ First guess profile for T, q: UM 6-11 hr forecast fields
  - ✓ First guess profile for O_3: climatology + OMI total ozone (-1d)
  - ✓ Background error covariance matrix: UM for T and q, ECMWF model for O_3
  - ✓ RTM: RTTOV v.11.2
  - ✓ Land surface emissivity: monthly climatology created from CIMSS IREMIS
- Algorithm Run-time configuration
  - ✓ RMSE Threshold for convergence: 1.0~1.3 K (clear), 1.5 K (cloudy)
  - ✓ Maximum number of iteration: 4
- Retrieved products show the potential benefits of using high-resolution geostationary imagery data for short-range severe weather forecast.
- Algorithm will be validated with longer-time period of data and performance will be enhanced by improving and adding input data (add 8.6 μm channel, apply accurate instrument error, improve ozone first-guess, etc.)

References

Cheng Da (2015) Preliminary assessment of the Advanced Himawari Imager (AHI) measurement onboard Himawari-8 geostationary satellite, *Remote Sensing Letters*, *6*:8, 637-646

EUMETSAT, 2013: MTG-FCI: ATBD for Global Instability Indices Product, EUM/MTG/DOC/10/0381

Hocking, J., P. Rayer, D. Rundle, R. Saunders, M. Matricardi, A. Geer, P. Brunel, and J. Vidot, 2014: RTTOV v11 Users Guide, WPSAF-MO-UD-028

JMA, n.d.: Imager(AHI). Meteorological Satellite Center(MSC) of JMA. Retrieved from: http://www.data.jma.go.jp/mscweb/en/himawari89/space_segment/spsg_ahi.html

LI, J., T. J. Schmit, X. Jin, and G. Martin, 2012: GOES-R Advanced Baseline Imager (ABI) Algorithm Theoretical Basis Document for Legacy Atmospheric Moisture Profile, Legacy Atmospheric Temperature Profile, Total Precipitable Water, and Derived Atmospheric Stability Indices. NOAA/NESDIS, Version 3.0, July 30, 2012

McPeters, R. D., and G. J. Labow (2012), Climatology 2011: An MLS and sonde derived ozone climatology for satellite retrieval algorithms, *J. Geophys. Res.*, *117*, D10303, doi:10.1029/2011JD017006

Lyu (2015) Current Status and Future Plan of KMA Satellite Program, presented at 2015 NOAA satellite Conference, April 27, 2015

Rodgers, C. D (1976), Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. Rev. *Geophys. Space Phys. 14*, 609-624

Rodgers, C. D. (2000), Inverse methods for atmospheric sounding: theory and practice, Singapore: World Scientific Press

Seemann, S.W., E. E. Borbas, R. O. Knuteson, G. R. Stephenson, H.-L. Huang, 2007: Development of a Global Infrared Land Surface Emissivity Database for Application to Clear Sky Sounding Retrievals from Multi-spectral Satellite Radiance Measurements. *J. of Appl. Meteor. and Climatol., Vol. 47*, 108-123

Xiaolei Z. and F. Weng (2015) Assessment of AHI Level-1 Data for HWRF Assimilation. Presented at The Sixth Asia/Oceania Meteorological Satellite Users' Conference, Tokyo, Japan, November 9-13, 2015

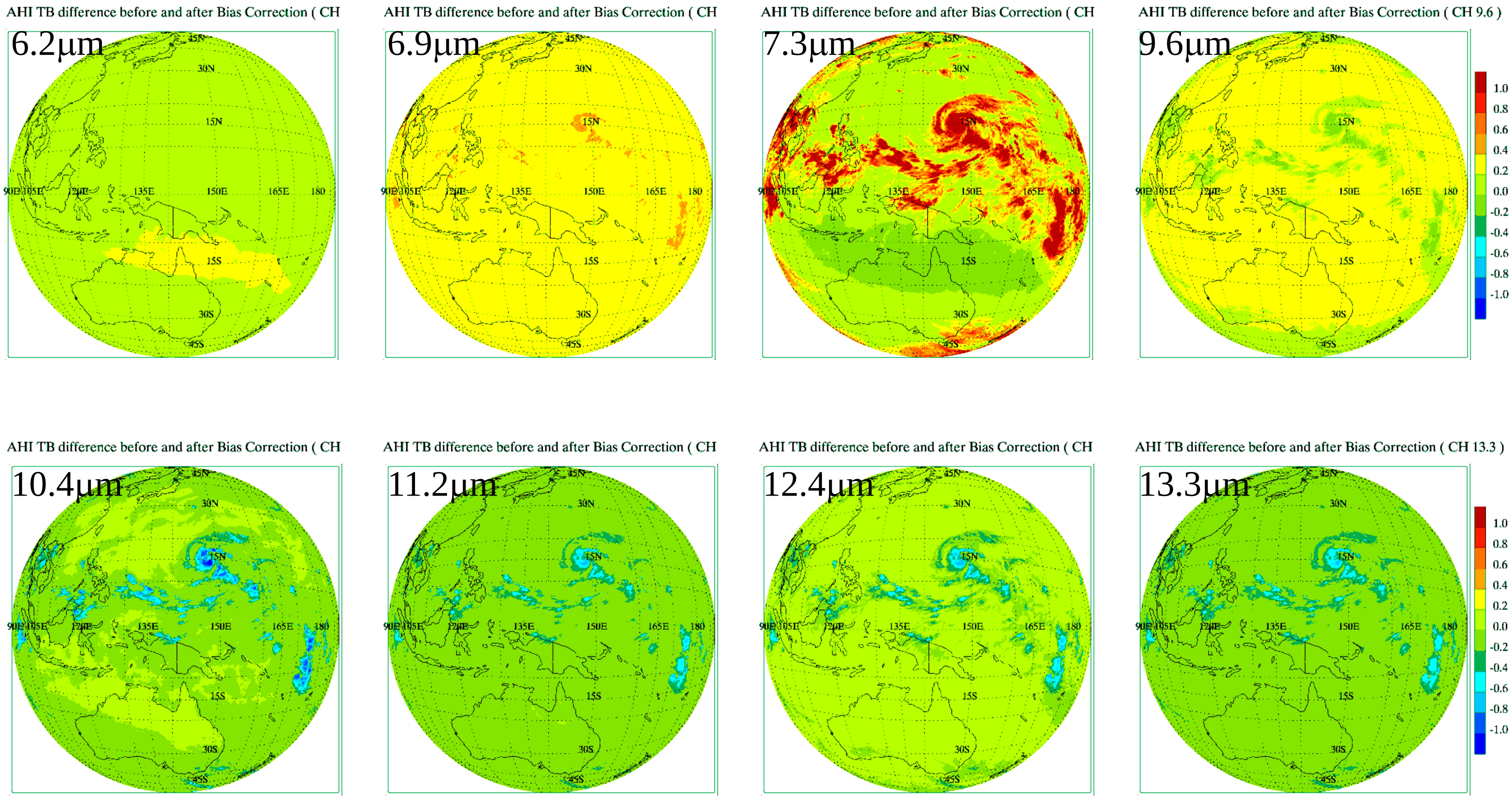
Thank you for your attention

Acknowledgement

This work was supported by "Development of OOO Algorithms" project, funded by ETRI, which is a subproject of "Development of Geostationary Meteorological Satellite Ground Segment (NMSC-2016- 01)" program funded by NMSC (National Meteorological Satellite Center) of KMA(Korea Meteorological Administration).

Performance factors – unbiased observation

➢ **TB difference before and after Bias Correction**



Error Analysis

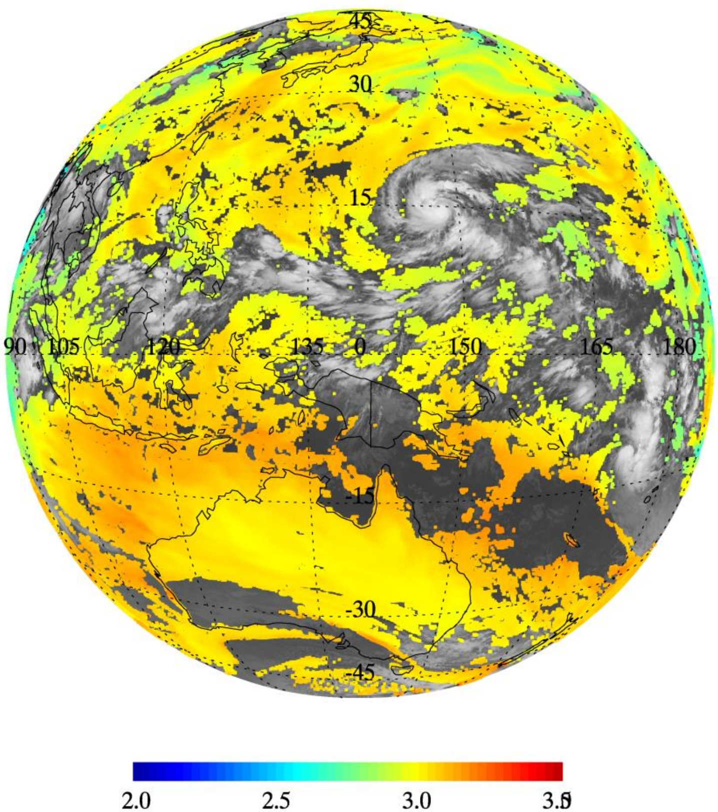
Degrees of freedom for signal

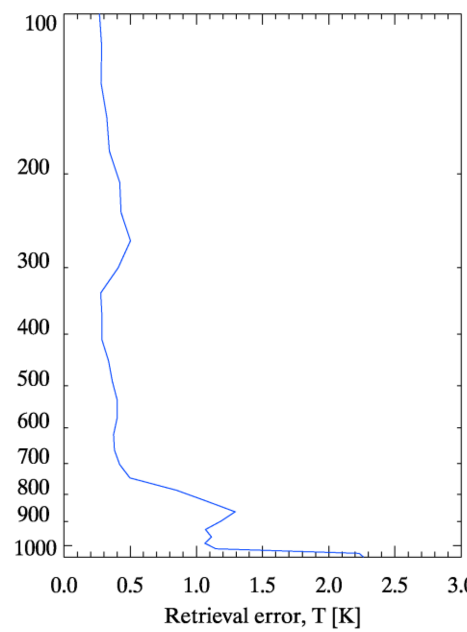
$$d_s = \mathrm{tr}(\underbrace{\boxed{\mathbf{S}_a\mathbf{K}^T[\mathbf{K}\mathbf{S}_a\mathbf{K}^T + \mathbf{S}_\epsilon]^{-1}}}_{\text{Gain}}\mathbf{K}) \qquad (2.54)$$

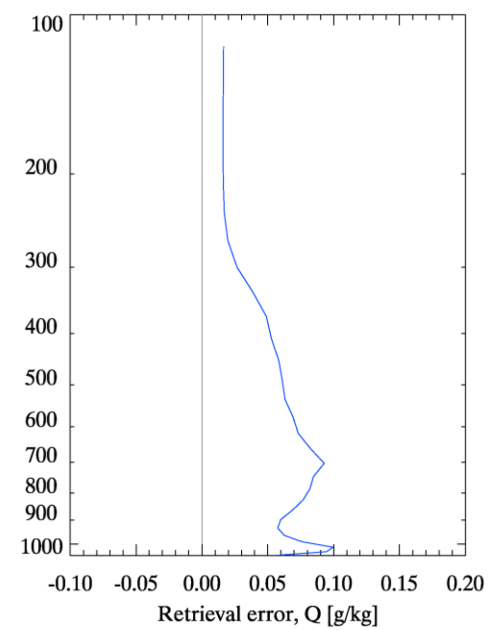
Retrieval error

$$(S_a{}^{-1} + K_n{}^T \cdot S_\varepsilon{}^{-1} \cdot K_n)^{-1}$$

Degrees of Freedom for Signal (20150802 00UTC)







Mean DFS: 3.0
Ranges: p.3 ~ 3.3

Data – 1. Sensor data

- **Radiance of 8 infrared channels measured from the Advanced Himawari Imager (AHI) of JMA as proxy to AMI**
  - ✓ **Comparison of GK-2A AMI and Himawari-8 AHI**

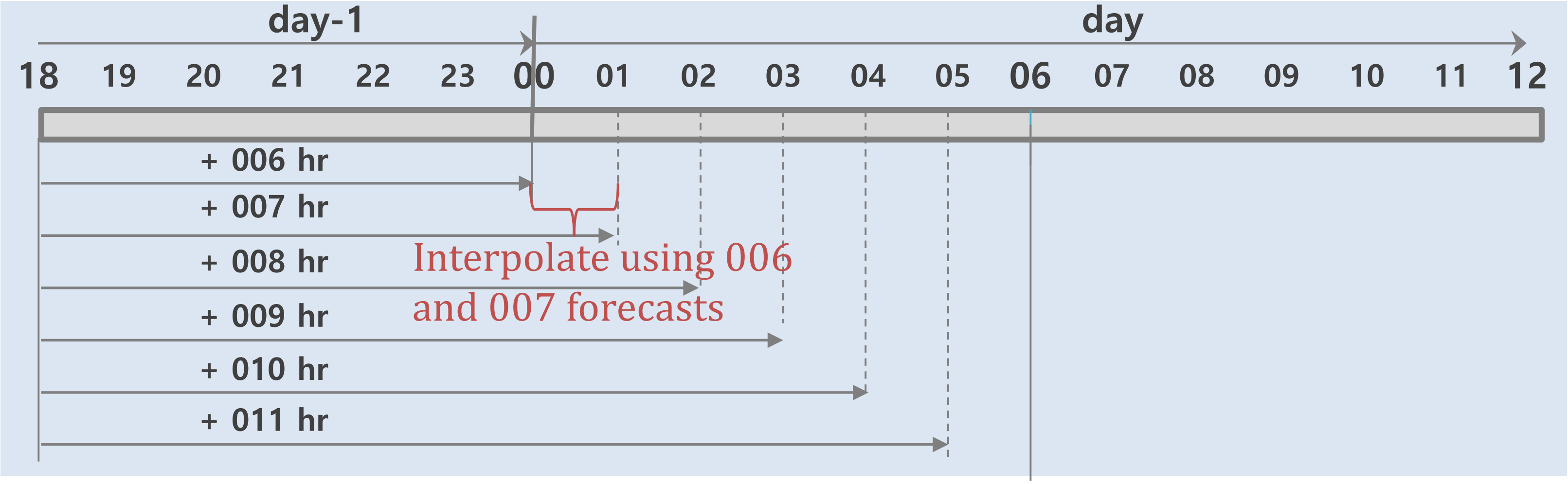
		GK-2A AMI	Himawari-8 AHI	
Infrared channels	8	6.24	**6.18**	√
	9	6.95	**6.95**	√
	10	7.34	**7.34**	√
	11	8.60	**8.60**	* over ocean only
	12	9.63	**9.61**	√
	13	10.4	**10.4**	√
	14	11.2	**11.2**	√
	15	12.3	**12.4**	√
	16	13.3	**13.3**	√
Sub-satellite point		128 E	**140.7 E**	
Spatial resolution (IR)		2 km	**2 km**	
Temporal resolution (FD)		10 min	**10 min**	

  - ✓ **Instrument (AHI) bias**
    - Study shows that scan-angle dependent bias is negligible (Cheng, 2015)
    - To get accurate instrument error(S_ε), GSICS* results will be used
    - Currently instrument error provided by WMO is used.

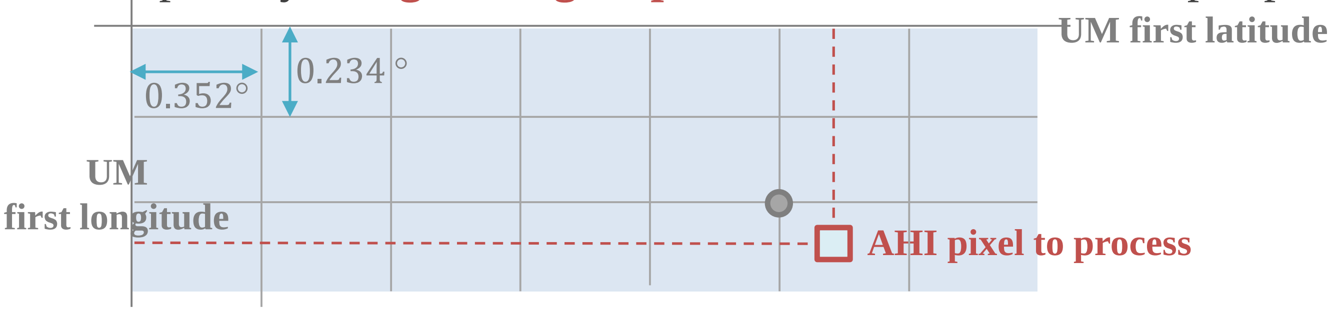
**GSICS: Global Space-based InterComparison System*

Data – 2. First Guess profile

- **Temperature and Moisture profile**
  - ✓ KMA **Global Model forecast** based on UK Met-office Unified Model (UM)
  - ✓ **6~11 hour** forecast fields with **1-hour interval**
  - ✓ Temporally **interpolate using 2 neighboring forecast fields**



  - ✓ Spatially, **assign UM grid point nearest** to the AHI super-pixel center



  - ✓ Vertical interpolation: linear for Temperature and cubic lagrange for mixing ratio

Data – 2. First Guess profile

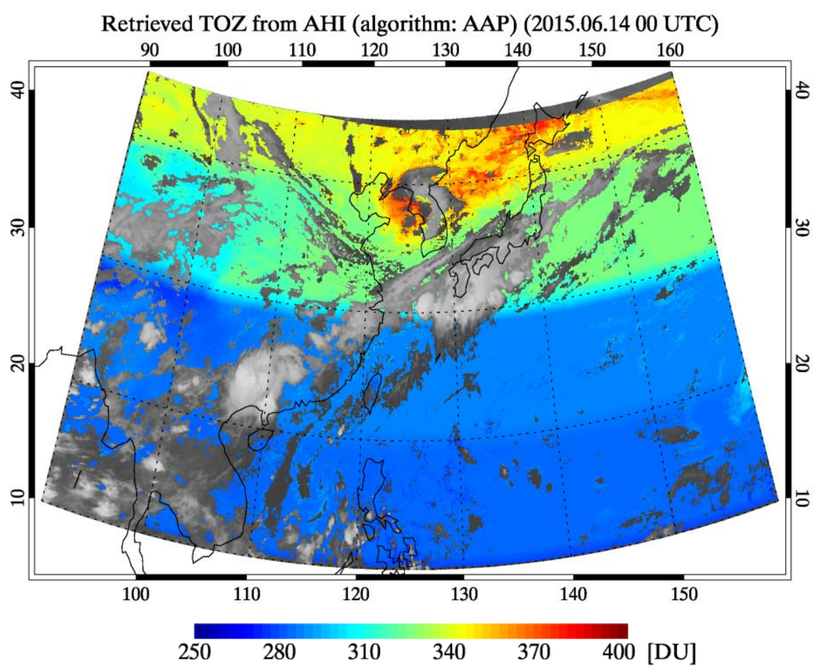
- Ozone profile

Before

Monthly Climatology with 10° latitude bands

(McPeters and Labow, 2012)

Ozonesonde (1988-2010) +
Aura MLS (2004-2010) data

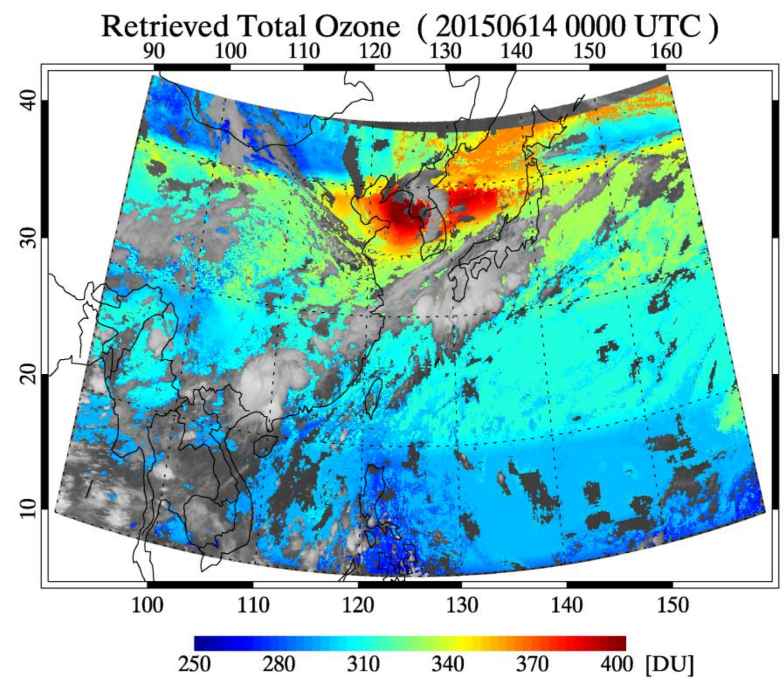


After (current configuration)

Monthly Climatology with 10° latitude bands

+

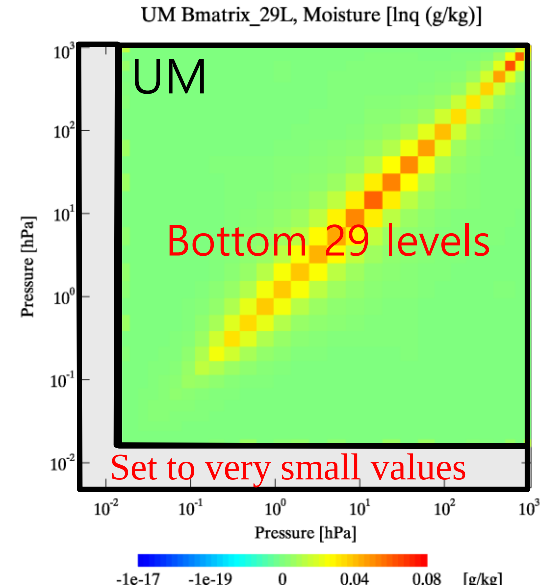
OMI Total Ozone (-1d)



Data – 3. Background Error Covariance (S_a)

- **(3L + 1) × (3L + 1) Matrix** (L=54, # of pressure levels)

UM L × L Temp./Temp. error covariance	L × L Temp./moisture error covariance (all 0)	L × L Temp./Ozone error covariance (all 0)	0 0 0 . . .
L × L Moisture/Temp. error covariance (all 0)	**UM** L × L moisture/moisture error covariance	L × L Moisture/Ozone error covariance (all 0)	. . . .
L × L Ozone/Temp. error covariance (all 0)	L × L Ozone/Moisture error covariance (all 0)	**ECMWF** L × L Ozone/Ozone error covariance	 0
0 0 0 0			SST/SST



* ECMWF (European Center for Medium-range Weather Forecast)